

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 26-09-2000		2. REPORT DATE TYPE ANNUAL		3. DATES COVERED (From - To) 01-07-1999 to 30-06-2000	
4. TITLE AND SUBTITLE MODELING FLUID-STRUCTURE INTERACTION				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER N00014-97-1-0017	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) HAYM BENAROYA TIMOTHY WEI				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) DEPT. OF MECH & AERO ENG RUTGERS UNIV 98 BRETT ROAD PISCATAWAY, NJ 08854				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) ONR BALLSTON TOWER ONE 800 N QUINCY ST ARLINGTON, VA 22217-5660				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER	
12. DISTRIBUTION AVAILABILITY STATEMENT UNLIMITED					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT THIS REPORT SUMMARIZES RESEARCH ACCOMPLISHED DURING THE PAST YEAR. ANALYTICAL AND EXPERIMENTAL WORK IS DESCRIBED WITH REFERENCES TO THE LITERATURE.					
15. SUBJECT TERMS 20000928 066					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU	5	HAYM BENAROYA
					19b. TELEPHONE NUMBER (Include area code) 732 445 4408

Modeling Fluid-Structure Interaction

Haym Benaroya
(732) 445-4408 [voice]
(732) 445-3124 [fax]
benaroya@rci.rutgers.edu

Timothy Wei
(732) 445-2718 [voice]
(732) 445-3124 [fax]
twei@rci.rutgers.edu

Department of Mechanical & Aerospace Engineering
Rutgers; The State University of New Jersey
98 Brett Road
Piscataway, NJ 08854-8058

Award #: N00014-97-1-0017

LONG-TERM GOALS

The principal goal of this program is on integrating experiments with analytical modeling to develop physics-based reduced-order analytical models of nonlinear fluid-structure interactions in articulated naval platforms. The critical research path for this effort is defined in the context of transitioning these models into engineering tools for design and analysis of existing and future marine systems. The symbiosis of analysis and experiments provides unique opportunities for advance the state-of-the-art in analytical modeling by directly addressing nonlinear coupling effects, and linking individual terms in the analysis to physical parameters measured in the laboratory. This research is also an excellent vehicle for training a new generation of workers who are adept at understanding fluid-structure interaction problems from both analytical dynamics and experimental fluid dynamics perspectives.

OBJECTIVES

The present modeling effort is concentrated on accurately describing the response of marine cables and structures to unsteady fluid loading. Sources of unsteadiness being considered include waves, currents, and vortex shedding. Note that these effects may be associated with natural oceanic phenomena or may arise from the engineering system itself (*e.g.* unsteady maneuvering of a towing vessel). All activities conducted in this program are framed in the context of the following scientific and technological objectives:

- Improve both analytical and experimental methodologies to support generalized modeling of fluid-structure interactions.
- Integrate experiments with analysis into reduced-order fluid-structure models.
- Advance the state-of-the-art in understanding of the non-linear coupling between fluid and structure motions.
- Transition fundamental results and methodologies into applications of immediate interest to the Navy.

APPROACH

Reduced-order analytical model development is being carried out using a Hamilton's principle based variational approach. This provides flexibility in the long run for generalizing the modeling paradigm to complex, three-dimensional problems with multiple degrees of freedom.

As both the experimental as well as analytical capabilities are advanced, the critical research path to integrating these components into reduced-order, fluid-structure interaction models entails:

- formulating a suitable, generalized, set of equations of motion,
- developing experimentally derived, semi-analytical functions to describe key terms in the governing equations of motion.
- using physical insight gained from both analytics and experiments to mathematically simplify the equations of motion without loss of accuracy,
- generalizing and transitioning the reduced-order model to specific engineering problems of naval relevance.

The specific problem being examined is the response of a 2.54 cm diameter, 150 cm long circular cylinder to its own vortex shedding. The cylinder, shown in Figure 1, has a mass ratio of 1.53 and a natural frequency of 1.25 Hz. It is attached to the floor of a large free surface water tunnel by a leaf spring aligned with the flow direction. The top of the cylinder protrudes through the free surface. In this configuration, the cylinder is free to oscillate like an inverted pendulum in response to Kármán vortex shedding.

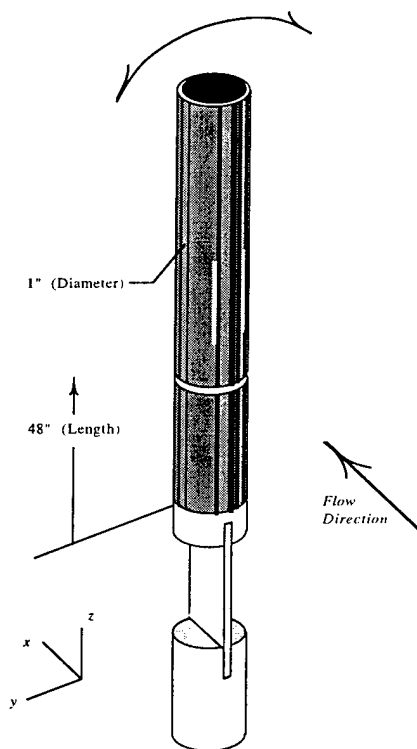


Figure 1: Schematic drawing showing the freely oscillating cylinder experiment.

WORK COMPLETED

The foci of this year's activities were divided between advancing analytical and experimental capabilities, exploring particular aspects of the freely oscillating cylinder problem, and linking to related NUWC projects. Accomplishments from this last year include:

Analytical

- developing capabilities to model wave/buoyancy effects,
- identifying approaches to incorporate variational mechanics into formulating the equations of motion,

Experimental

- examining free surface effects on vortex shedding,
- developing capabilities to measure around the cylinder,

Transition

- strengthening linkages to the NUWC-MLTA effort.

Details of analytical and experimental progress appear in the following section. A discussion of the MLTA work appears in the RELATED PROJECTS section.

RESULTS

One of the most significant milestones in FY00 was the formalization of the integrated experimental-analytical modeling paradigm in a paper by Benaroya & Wei (2000). This work is scheduled to appear in the *Journal of Sound and Vibration*. With this framework in place, both the analytical and experimental components were focussed toward expanding capabilities and gaining greater insight into the freely oscillating cylinder problem. Following the bullet items in the preceding section, details of each activity are presented below.

Developing Capabilities to Model Wave/Buoyancy Effects

The dynamic responses of a compliant ocean tower such as an articulated tower or a tension leg platform were examined in Han, *et al.* (1999) and Han & Benaroya (2000a,b). A vertical member in such a structure was modeled as a cylindrical beam supported at the base by a torsional spring. Static forces were introduced through a buoyancy chamber and a point load at the top. Major dynamic forces were due to waves and current¹.

For the purposes of advancing analytical capabilities in anticipation of future integrated modeling, fluid loading was modeled using the Morison equation. In the present mathematical model, the beam element was allowed to stretch so that both axial and transverse displacements were part of the dynamics. In some cases, nonlinear axial motions, known as springing and ringing, were observed, and they may play an important role in the overall dynamics. Axial motions were also found to be significant and therefore should be monitored and controlled so that comfort of the crew on an offshore platform can be ensured.

Incorporating Variational Mechanics into the Equations of Motion

In Benaroya & Wei (2000), the McIver-Hamilton Principle was extended to include external flows. The result was an energy-based framework for describing fluid flow about elastic structures. Experiments are being conducted at this writing to provide a complete data set for the freely oscillating cylinder problem.

A key result of this analysis was the identification of two distinct approaches to deriving the framework depending on how the boundary conditions are interpreted. The first approach does not require *a priori* knowledge of boundary conditions. In this case, only a single mechanical energy equation is derived which describes the position of the structure as a function of time. This appears in Benaroya & Wei (2000) and was also reported in the FY99 end of the year report.

The second approach would be to use concepts from variational mechanics; this requires knowledge of the boundary conditions at arbitrary times, t_1 and t_2 . For external flows with an arbitrary fluid control volume, it is not clear what those boundary conditions should be. The distinct advantage, however, is that it yields a full system of equations which may be generalized to complex geometries and flows. It is important to note, that regardless of the approach used, *i.e.* whether or not boundary conditions are prescribed, non-linear couplings between fluid and structure are inherently included in the model equations(s).

¹ In this analysis, the structural motion was confined to a plane. Consequently, we have considered only two-dimensional fluid current and wave forces.

Developing Capabilities to Measure Fluid Velocities Around the Cylinder

One feature of the analytical model is the definition of a 'closed' control volume containing the structure that is surrounded by an 'open' control volume of prescribed dimensions through which fluid flows. It is therefore a necessary requirement for the experiments to obtain velocity fields around and including the circumference of the cylinder.

To this end, significant changes in the physical experiment were made including replacing the aluminum cylinder with Plexiglas, changing the leaf spring, and using a Nd-YAG laser. A sample vector plot containing the full the cylinder appears in Figure 2. At this writing, a complete data set (~60 sets of ~200 DPIV image pairs sampled at 10 Hz) has been obtained for use in the reduced-order model.

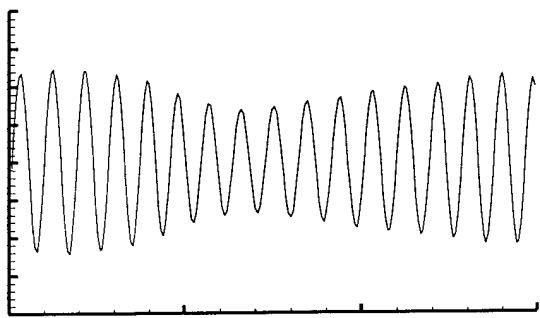


Figure 3: Sample amplitude vs. time trace for the freely oscillating cylinder in the maximum amplitude response case. The modulation in amplitude is coupled to the direction of axial flows in the Kármán vortices.

close to the free surface, there was an equal likelihood of strong down-flows away from the surface. Closer examination indicated that up-flows correlated to times when the modulating cylinder amplitude increased, Figure 3. Down-flows occurred with decreasing amplitude. The extent of the free surface effects is on the order of tens of centimeters, and is therefore of significant interest to this modeling effort. Further study of this problem will continue in FY'01.

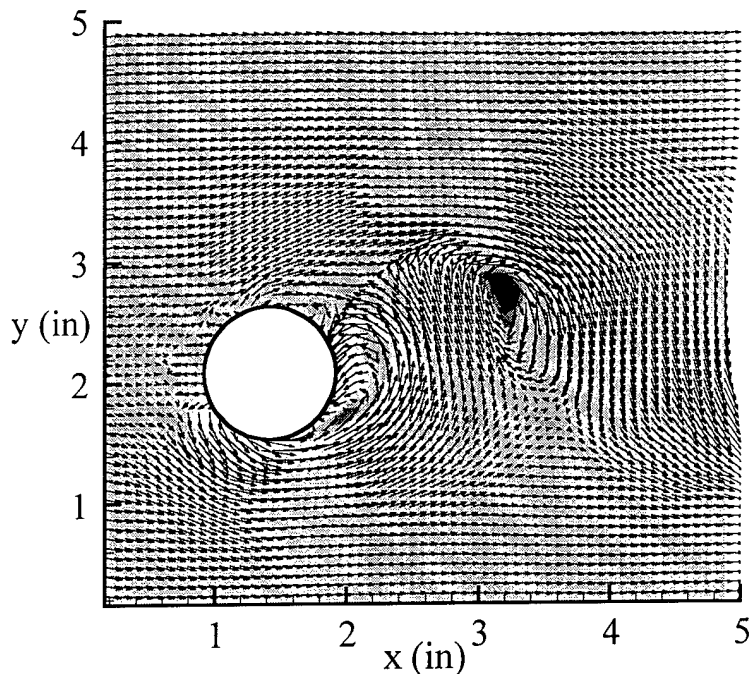


Figure 2: Instantaneous DPIV vector field obtained with the cylinder within the field of view. This permits use of control volumes which completely surround the structure. The reference frame is moving at $1/2 U_{\infty}$.

Examining Free Surface Effects on Vortex Shedding

This component of the research was motivated by free surface-turbulent boundary layer research reported in Hsu, *et al.* (2000). At issue was determining the degree to which the free surface influenced vortex shedding, *i.e.* energy transport, in the oscillating cylinder experiment.

Flow visualization experiments indicated strong axial flows develop in the Kármán vortex cores within 2-3 diameters of the cylinder. Far from the free surface, these flows were predominantly upward toward the free surface. This could be explained by axial vorticity gradients induced by the pendulum-like cylinder motion. However,

IMPACT/APPLICATIONS

A deeper understanding of fluid-structure interactions can have extensive impact on both military and civilian technology. A specific case is the ongoing MLTA work outlined in the RELATED PROJECTS section. The dynamics of flow-induced vibration affects the design of everything from aircraft and skyscrapers to ships. Uncertainties associated with these interactions are difficult to quantify and require a deeper understanding as structures are required to operate in more severe environments under stricter constraints. The variational mechanics framework is a very exciting one, in that it provides a high level perspective on physical processes (*i.e.* solid, fluid, and their interaction) and how to model them. The equations of motion derived this way can be interpreted to include random loading effects.

TRANSITIONS

Over the past year, fundamental scientific findings and methodologies have been transitioned into the technology arena. Specifically, direct connections to the Navy's MLTA development effort as well as to the paper industry have been established. The modeling paradigm is also being broadened to include hydroacoustics and two-phase flow problems. Scientific findings from this investigation are being disseminated through refereed journal articles and international conference papers. In addition, the PIs have been invited to give a number of seminars.

RELATED PROJECTS

There are two ongoing interactions with Navy laboratories that are directly relevant to this program. The first is a collaboration with NUWC on the dynamics of multi-line towed sensor arrays. In the past year, funding from NUWC was used to examine the dynamic response of a towed cable model subject to periodic forcing. Under certain conditions, the cable response is highly non-linear and may be chaotic. It was noted that the transverse cable motions were analogous to the freely oscillating cylinder experiment being conducted under this grant. As noted previously, there is now an integral linkage between this basic research effort and an ongoing Navy systems development program. A second collaboration is being developed with the Structural Acoustics and Hydroacoustics Branch at NSWC. Building on the modeling paradigm, fluid-structure interactions are being examined in the context of flow noise generation.

PUBLICATIONS

- Benaroya, H. & Wei, T. 2000 Hamilton's principle for viscous external fluid-structure interaction. *J. Sound and Vibration* (in press).
- Deng, P., Hsu, T.Y., Atsavapranee, P. & Wei, T. 2000 Digital particle image accelerometry. *Expts. in Fluid* (in print).
- Han, S., Benaroya, H. & Wei, T. 1999 Dynamics of transversely vibrating beams using four engineering beam theories. *J. Sound and Vibration*, **225**, 935-988.
- Han, S. & Benaroya, H. 2000a Nonlinear coupled transverse and axial vibration of a compliant structure I: Formulation and free vibration. *J. Sound and Vibration* (in press).
- Han, S. & Benaroya, H. 2000b Nonlinear coupled transverse and axial vibration of a compliant structure 2: Forced vibration. *J. Sound and Vibration* (in press).
- Hsu, T.Y., Grega, L.M., Wei, T., & Leighton, R.I. 2000 Turbulent kinetic energy transport in a corner formed by a solid wall and a free surface. *J. Fluid Mech.* **410**, 343-366.